Theoretical Issues in Ergonomics Science
Vol. ??, No. ?, Month?? 2008, 1–25

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Genotype and phenotype schemata and their role in distributed situation awareness in collaborative systems

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(*Received 12 September 2007; final version received* [redacted])

Situation awareness (SA) is a critical commodity for teams working in complex systems. This article builds on existing schema theory to postulate an explanation of how teams develop and maintain SA during collaborative activities. The perceptual-action cycle approach and schema theory are used to formulate a model of distributed SA. Extracts from a case study undertaken in the UK energy distribution domain are used to demonstrate the concept of genotype and phenotype schemata as distributed SA. The sub-concepts of compatible and transactive SA are also outlined and explored via the case study. The differences between this perspective and the more commonly cited 'shared SA' perspective is articulated. In conclusion, whilst the ideas presented in this article are quite different to those expressed by the dominant models of individual and team SA presented in the literature, it is contended that they are more appropriate for the study of SA in collaborative environments.

Keywords: situation awareness; teams; schema theory; genotypes; phenotypes

1. Introduction

The inescapable conclusion reached by the present authors in a recent review of situational awareness (SA) theories and approaches (Salmon *et al.* 2008a) was that, despite its recognised importance within system design and evaluation, there are still several prescient issues that need to be confronted. Does good SA equal good performance? Does the quantity of SA relate to its quality (or is it the other way around)? Is SA something that resides in people's heads or in the world, or both? Situation awareness, therefore, remains a contentious topic.

SA's legacy in aviation is clearly evident in some of the more popular approaches. SA is seen as an individual phenomenon; in other words, is something that resides in people's heads. The use of an underlying information-processing model of cognition has tended, again, arguably, to bestow upon the concept not just a feeling of 'individuality' but also a certain feeling of 'linearity' too: more SA is better SA. No more are these issues evident than in popular approaches to SA measurement, most of which seem to work on these tacit principles (e.g. situation awareness global assessment technique (SAGAT); Endsley 1995). Given that the vast majority of domains within which SA issues are critically

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ISSN 1463–922X print/ISSN 1464–536X online

DOI: 10.1080/14639220802045199
http://www.informaworld.com

important involve teams, not individuals, it is hardly surprising that this approach has been extended and it is here that the limitations of underlying theories and concepts become particularly manifest. Casting the theoretical net wider quickly reveals that SA need not be something that resides in the heads of individuals but could be embedded in the context as well (e.g. Hutchins 1995). More does not necessarily mean better either (Chase and Simon 1973) and the inherent complexities brought by team working bring with them a corollary in the form of an Aristotilean 'non-linearity'. SA, like teams themselves, may be more (or less) than the sum of its parts. So, clearly, there is justification in exploring these limitations, learning from them and finding theoretical approaches that provide a better characterisation of the problem that team working presents. It is to this that the current article now turns. Three strands of thinking are brought together: schema theory, the twin notions of genotype and phenotype schemata, the mapping of these concepts onto Neisser's (1976) perceptual cycle model of cognition and, in turn, the mapping of these concepts onto SA. A case study from the energy distribution domain serves to demonstrate schema-driven awareness, compatible and transactive SA and how the approach developed in the paper responds to the challenges of analysing team SA.

2. Introduction to schema theory

Schema theory first emerged in the early 1900s (e.g. Head 1920, Piaget 1926) and describes how individuals possess mental templates of past experiences, which are mapped with information in the world to produce appropriate behaviour. Bartlett (1932) introduced the concept of 'schema' as active organisations of past reactions and past experiences, which are combined with information in the world in order to produce behaviour. A schema, therefore, is rather like a form of mental template; it is clearly 'more than a "set" because it is more elaborate and less restricted to a particular situation; it is more ideational or implicit than a "strategy" and conceptually richer than a "hypothesis"' (Reber 1995, p. 689). Bartlett (1932) used the example of cricket to demonstrate how, when making a stroke, a batsman is not producing entirely new behaviour nor is he merely repeating old behaviour. Rather, Bartlett (1932) suggests that the stroke is 'literally manufactured out of the living visual and postural "schemata" of the moment and their interrelations' (Bartlett 1932, p.201). Bartlett's example demonstrates how schemata in the mind of the individual combine with their goals, the tools that they are using and the actual situation in which they are placed in order to generate behaviour. Bartlett (1932) further investigated the concept and the role of schemata in an individual's recall of events by undertaking a series of studies on the processes of remembering and forgetting. In conclusion, Bartlett (1932) argued that literal recall was very rare and rather that recall was a process of reconstruction and that memories showed evidence of consolidation, elaboration and invention, using material from other schemata.

Bartlett subsequently argued that schemata allow individuals to orientate themselves toward incoming stimuli and adapt their responses to it. This frame of reference can work to the advantage or disadvantage of the individual. If the schema is appropriate to the situation, then an appropriate response may be produced. Norman (1981), however, has suggested that the 'triggers' of the situation may be wrongly interpreted, leading to a maladaptive response. Schemata are not necessarily open to conscious examination, so the question of identification and adaptation of more appropriate schemata is a moot point. The schema themselves are unlikely to exist as separate sets of templates, but rather as an interconnecting set of structures, of which aspects are triggered in response to a particular set of circumstances or experiences. Thus, one could view the activates aspects of schemata as structures that move in and out of pre-conscious (and possibly conscious) attention like the brightening and dimming of variable lighting. Niesser (1976) suggests a hierarchical arrangement of embedded schemata and their associated actions. As proposed by schema theorists (Bartlett, Piaget, Neisser and Norman), the schemata are continually modified through interaction with the world in which behaviour is created.

Anderson (1977, pp. 418–419) suggested that there are five main defining features of schemata. These include that the schemata: (1) are organised meaningfully in some way; (2) are embedded within other schemata and contain sub-schemata themselves; (3) change from moment to moment as information is received; (4) are reorganised when incoming data reveal a need to restructure; and (5) are gestalt mental representations. These features allude to the dynamic, non-linear and personal nature of schemata, which is why Bartlett noted that memories of events (even learning of stories) take on such an individual nature when recalled. They also account for the performance differences between novices and experts; as experts might not only be attending to different stimuli (as directed by their schemata), but also deriving different types of understanding through their interaction. Further, the gestalt nature of the schema could mean that experts are able to infer more than simply the bare facts might suggest, implying a higher level of understanding can be derived though richer schemata and interactions.

Norman and Shallice (1986) used the ideas behind schema theory to develop a cognitive model of attention and control that could be used to explain everyday behaviour. Norman and Shallice distinguished between automatic and willed control and argued that schemata are templates for behaviour that are triggered by cues in the environment. Although several schemata might be activated at any moment in time (offering a range and variety of possible behaviours), the selected schema will be automatically allocated on the basis of the strength of activation and motivations of the individual. Controlled processes are only activated when the task becomes too difficult, such as novel situations or when errors are made.

Schema theory is well established in the psychology literature and has been applied to the description of everyday activities, such as clinical therapy (Young *et al*. 2003), learning (Wood 1998), driving (Hole 2007) and tool use (Baber 2003).

2.1. *Genotype and phenotype schemata*

Baber and Stanton (2002) describe the concepts of global prototypical routines (GPRs) and local state specific routines (LSSRs) in order to explain how individuals interact with products and devices. They suggest that individuals use GPRs and LSSRs to direct their interactions with products and devices and that GPRs represent the schemata in the mind of the person, whereas LSSRs represent the activated schema brought to bear on a specific problem by a user. Similar to Bartlett (1932), they suggest that the schema is reconstructed with the current stimuli and that the ensuing interaction leads to the modification of the schema toward the goals (although even the goals are subject to change in light of the interaction). GPRs represent stereotypical responses to system images that a person has learned, acquired or otherwise developed (Baber and Stanton 2002). Examples of GPRs include a strong stereotyped response to turn a tap (faucet) counter-clockwise to turn it on or to increase water (Sanders and McCormick 1992, cited Baber and Stanton 2002). Regardless of whether these responses are correct, it is important to note that individuals typically attempt them before any other actions (Baber and Stanton 2002). Baber and Stanton (2002) also propose that individuals possess LSSRs, which involve the generation of appropriate actions through the individuals interpretation of a device's 'system image' in relation to the current goal state (Baber and Stanton 2002). LSSRs are therefore dependent upon the information that is available through the system image. Baber and Stanton (2002) suggested that designers of those public technologies that expect people to use them accurately the first time, without any instruction (such as food vending machines, ticket machines and automated teller machines), need to capitalise on triggering appropriate GPRs and supporting the user in adapting LSSRs.

GPRs are rather like the genotype schemata and LSSRs are rather like the phenotype schemata proposed by Niesser (1976). Genotype, in this context at least, refers to the wider systemic factors that influence the development of individual cognitive phenomena and behaviour. The local, individual-specific manifestation of cognition and behaviour represents the phenotype. Hollnagel (1998) used the genotype and phenotype distinction to illustrate generic error modes (the genotype) and how they may be related to observed errors (the phenotype) in the world. Hollnagel's model suggests that the combination of genotypes (man, technological and organisational), the environment and random variation produces the phenotype, which is the observable manifestation of the error. It is apparent that, more often than not, devices fail to trigger appropriate schemata in their users. Norman (1981) used schema theory to explain erroneous actions, such as slips of action or lapses in attention. His analysis suggested that three basic genotype schema-related errors can account for the majority of errors. These were activation of wrong schemata (due to similar trigger conditions), failure to activate appropriate schemata (due to a failure to pick up on the trigger conditions indicating a change in the situation) and a faulty triggering of active schemata (triggering the schema either too early or too late to be useful).

3. Neisser's perceptual cycle

Neisser's (1976) seminal work *Cognition and reality* is perhaps the most commonly used and cited text on schemata. Within this text, Neisser described the concept of the perceptual-action cycle, which included the notion that anticipatory schemata, held by individuals, served to anticipate perception and direct action. Heavily based on the work of James and Eleanor Gibson, Neisser proposed the ecological view in juxtaposition to the information-processing view. The ecological approach suggested that perception was an active, rather than a passive, process and that perception could be viewed as guided exploration in the sense that the active schemata direct where one looks/listens/touches and what one expects to see/hear/feel. This exploration leads to adaptation to the environment by the perceiver, which guides future exploration. Neisser adopts the view that interaction with the world is cyclical in nature rather than linear, as implied by an information-processing chain. The schemata are the active knowledge structures that guide the exploration and interpretation of the information, which in turn changes those structures, further guiding exploration, and so on. The form and nature of the schema will determine what one is able to perceive through this interaction, i.e. how it fits into one's own personal schemata. Neisser argues that schemata interact with the temporal nature of events, by linking the past to the future in two main ways. First, the anticipation of what will happen next determines what one does: what information one looks for and attends to. Second, one understands the stream of activity though the anticipation (and continuous modification of that anticipation) to make sense of the events as they unravel through the interaction. One sees/hears/feels/smells/tastes the whole experience in terms of its meaning to each person as an individual.

Neisser considered the multiplicity of information and integration of the modalities essential to the interpretation of the experience. Thus, schema-based theories tacitly assume that cognition is not only cyclical (rather than linear) but also parallel (rather than serial). The schemata are modified by the experience, but themselves are also modifying the experience, creating a better situation for the individual to be aware of. In this way, Neisser links cognitive activity to physical behaviour to exploration and interaction in the world. To a psychologist, the perception-action cycle together with schema theory offers a theory-of-everything. It explains the way in which the world constrains behaviour as well as how cognition constrains one's perception of the world. It explains both top-down and bottom-up processing of information, but also shows that everyday behaviour is formed through a mixture of both approaches. Whether one processes features or meaning extracted from features depends upon which sort of perceptual cycle one is in, which in turn directs 'information pick-up' next time around. Hollnagel (1993) proposed the perceptual cycle as a fundamental unit of analysis in the assessment of 'joint cognitive systems', such as found in human–computer interaction.

3.1. *The perceptual cycle and situation awareness*

The time has come to try and weave these disparate strands together and map them onto the comparatively modern concept of SA. Indeed, it is only in the last decade or so that considerable interest in the concept of SA, as a means of explaining how humans and technology interact, has arisen. Various models have been proposed (see Salmon *et al.* (2008a) for a critical review) and it is likely that debate over their efficacy will continue in academic circles for quite some time (e.g. Artman 2000, Shu and Furuta 2005, Gorman *et al*. 2006, Patrick *et al*. 2006, Salmon *et al*. 2006, Siemieniuch and Sinclair 2006, Stanton *et al*. 2006, etc.). Be that as it may, two models can be singled out as representing particular counterpoints from a theoretical point of view: the model of SA expounded by Smith and Hancock (1995), based on Neisser's perceptual cycle (1976) and, by far the most popular, Endsley's three-level model. The two approaches, shown in Figure 1, lead to two distinct definitions of SA:

(1) Smith and Hancock (1995) define SA as: 'adaptable, externally-directed, consciousness' (p. 135).
(2) Endsley defines SA as: 'The perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future' (Endsley 1995, p. 36).

In both cases the reader is referred to Salmon *et al.* (2008a) for an in-depth description of the two models.

4. Genotype and phenotype schemata

Given the foregoing discussion, it should come as no surprise that the perceptual cycle approach is felt to be the most appropriate for taking forward for use in considering team SA. The approach fits with a wider, increased level of emphasis placed on the collective behaviour of systems as a whole, as opposed to the behaviour of the individuals working

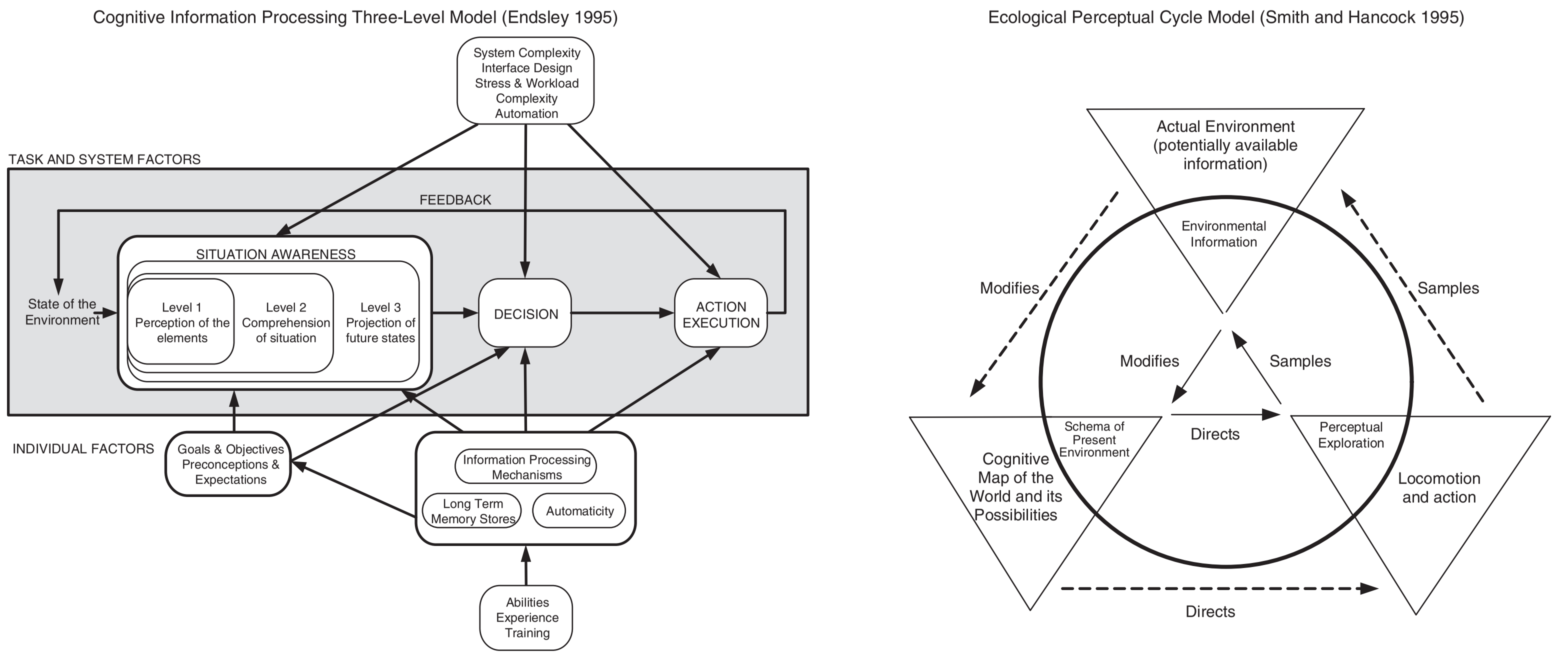

Figure 1. Information processing view *vs* the perceptual cycle view of SA.

within the system (e.g. Hollnagel 1993, Hutchins 1995, Artman and Garbis 1998, Ottino 2003). The work of Hollnagel (1993) reflects this trend. For example, he notes that the 'unit of analysis' of team work has to be higher than the level of the individual. Indeed, Hollnagel's well-known 'contextual control model' was used to describe the mode of activity 'the team was in', rather than describing the activities of any of its members. Artman and Garbis (1998) also argue that when considering team performance in complex systems, it is necessary to focus on the joint cognitive system as a whole and that in domains such as the military, teamwork is essential for success. The corollary of this, as Ottino (2003) states, is that complex systems cannot be understood by studying their parts in isolation, rather that the real meaning of the system lies instead in the interaction between its parts and the resultant behaviour that emerges from these interactions. Thus, a non-individual approach to the assessment of SA fits well with wider movements in the literature.

Neisser's ecological approach to describing how individuals acquire and maintain SA is compatible with this trend. It purports that SA is neither resident in the world nor in the person, but resides through the interaction of the person with the world. Smith and Hancock (1995) argue that the process of achieving and maintaining SA revolves around internally held schemata, which facilitate the anticipation of situational events, direct attention to cues in the environment and direct eventual course of action. Checks are then made to confirm that the evolving situation conforms to one's expectations. Any unexpected events serve to prompt further search and explanation, which, in turn, modifies the existing schema.

Smith and Hancock (1995) therefore identify SA as a subset of the content of working memory in the mind of the individual (in one sense it is a product). However, they emphasise that attention is externally directed rather than introspective (and thus is contextually linked and dynamic). Relating Smith and Hancock's model to genotype and phenotype schemata suggests that individuals possess genotype schemata that are triggered by the task-relevant nature of task performance. During task performance, the phenotype schema comes to the fore. Although these genotype and phenotype schemata may not be open to analysis, it could be argued that it is likely that the phenotype schema may be inferred though a variety of data collection methods. Smith and Hancock argue that the 'unit of analysis' should be at the level of the interaction between agents and artefacts, rather than individual consideration of each separate component. The perceptual cycle offers insight into this interaction as well as defining how agents maintain an awareness of changing situations, on a moment-by-moment basis. Adams *et al.* (1995) argue that the perceptual-action cycle illustrates how it is possible for people to maintain SA: 'provided that the flow of data is manageably paced and reasonably compatible with the knowledge and experience constituting the perceiver's active schema' (Adams *et al.* 1995, p. 90). The present authors suspect that when the workload is too high to maintain awareness, people revert to genotype schemata, as it may not be possible to maintain the phenotype. Hole (2007), for example, notes that cognitive theorists (e.g. Norman and Shallice 1986) propose separate supervisory and scheduling sub-systems that attempt to resolve conflicts in attentional demands.

5. Shared SA?

Many attempts have been made to explain the SA of teams working together in complex systems (e.g. Wellens 1993, Salas *et al.* 1995, Endsley and Jones 1997, Artman and

Garbis 1998, Endsley and Robertson 2000, Shu and Furuta 2005, Stanton *et al*. 2006, etc.). Most attempts have focused on the concept of 'shared' SA. Some definitions may help to clarify what is meant by 'shared':

- Nofi (2000, p. 12) defines team SA as 'a shared awareness of a particular situation'. But does shared SA mean identical SA? If so, to what extent?
- Stout *et al*. (cited Salas *et al*. 2006) suggest that team SA comprises each team member's SA and the degree of shared understanding between team members. Shared awareness still appears as a relatively blunt characterisation: what might it comprise?
- Endsley and colleagues (Endsley 1989, Endsley and Jones 1997, Endsley and Robertson 2000) explicitly distinguish between shared and team SA. Shared SA is defined as: 'the degree to which team members have the same SA on shared SA requirements' (Endsley and Jones 1997). Team SA, on the other hand, is defined as: 'the degree to which every team member possesses the SA required for his or her responsibilities' (Endsley 1989).

Shared SA accounts, certainly those inspired by Endsley (1989, 1995), suggest that during team activities SA overlaps between team members, in that individuals need to perceive, comprehend and project SA elements that are specifically related to their role within the team, but also elements that are required by themselves and by other members of the team. Successful team performance therefore requires that individual team members have good SA on their specific elements and also the same SA for shared SA elements (Endsley and Robertson 2000). The shared SA view is presented in Figure 2.

It is apparent that there is significant incongruence between the ideas of team members' genotype and phenotype schemata driven awareness of a situation and the shared SA view. According to the perceptual-action cycle view, each team member constructs their own personal mental theory of the situation, perception becomes reality and the situation,

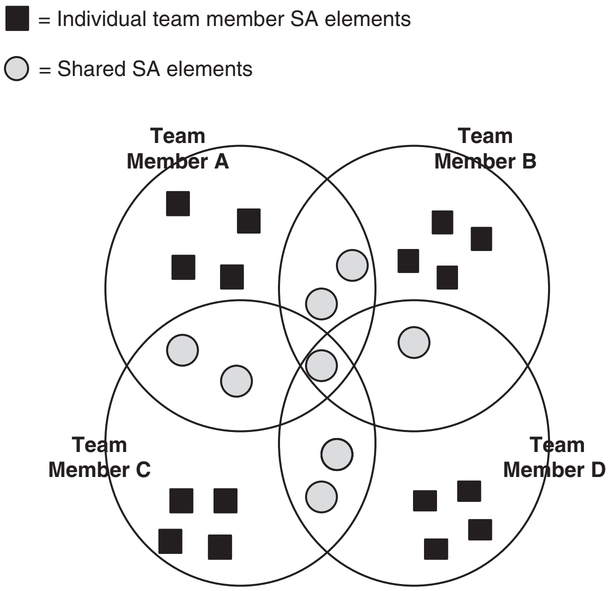

Figure 2. Shared SA (adapted from Endsley 1995).

whatever that may be, is modelled differently by each team member. Of course, there may well be circumstances where considerable overlap in awareness is achieved (and methods aimed at diagnosing such instances will have worthwhile intervention effects) but this seems unlikely given the inevitable variability in goals, roles, experiences, training, knowledge, skills and attitudes across the team. The role of personalised genotype and phenotype schemata, therefore, makes the idea of 'identical' and thus 'shared' SA seem questionable. The key point seems to be that the presence of different goals, roles, experiences, etc. across team members suggests that each team member's genotype schema will be unique, regardless of whether the information that they are exposed to is identical.

To explore this idea further, the concept of distributed SA (DSA) is put forward (Artman and Garbis 1998, Stanton *et al*. 2006, Salmon *et al*. 2008b). DSA is currently receiving increased attention from the human factors and ergonomics community (e.g. Masys 2005, Stanton *et al*. 2006, Hazlehurst *et al*. 2007, Salmon *et al*. 2008b, etc.). These approaches are born out of the same notion that has enabled the discussion so far to progress to this point. Put simply, in order to fully understand behaviour in collaborative environments, it is the system itself rather than the individuals within it that should be taken as the unit of analysis.

DSA models are underpinned by distributed cognition theory (Hutchins 1995) and cognitive systems engineering (e.g. Hollnagel 1998) approaches, both of which focus on cognition at the systems level, suggesting that the agents and artefacts comprising a system conjugate together to form a so-called 'joint cognitive system' and that cognitive processes emerge from and are distributed across this joint cognitive system. Cognition is therefore achieved through coordination between system units (Artman and Garbis 1998) and is treated as a systems endeavour. Emphasis is placed particularly on the idea of 'coordination'.

DSA therefore operates at a systems level and takes a very different perspective to the individual and shared SA approaches presented in the wider literature. As such, it is possible that shared SA approaches could misdirect attention to inappropriate aspects of the task. There are points in tasks where SA may appear to overlap for brief periods in distributed team working but it is argued here that this is where so-called transactions in awareness occur. Furthermore, it can be contended that DSA requirements are not the same as shared SA requirements. Shared SA implies shared requirements and purposes, whereas DSA implies different, but potentially compatible, requirements and purposes. The approach here assumes, therefore, that DSA can be defined as activated knowledge for a specific task within a system (Stanton *et al*. 2006). Taking this notion into the realm of distributed cognition makes it possible to propose that a situation requires the use of appropriate information (held by individuals, captured by devices, etc.) that relates to the state of the environment and those changes as the situation develops. For the model presented in this paper, the 'ownership' of this information is initially at the system, rather than individual, level.

6. Compatible awareness and transactive tokens

The concepts of compatible SA and transactive SA elements require further exploration in relation to genotype and phenotype schema theory. First, within DSA it is possible to think of compatible awareness and transactive tokens, rather than a sharing of awareness. Compatible awareness is the phenomenon that holds a distributed system together. Each agent in the system has their own awareness, related to the goals they are working towards.

This is not the same as other agents, but it is such that it enables them to work with the agents adjacent (in terms of the temporal nature of tasks) to them. Awareness is not shared as described in Endsley's account, since each team member's view on the situation is different, despite using the same information as one another. Team members may exchange information with one another (through requests, orders and situation reports), which is where the idea of a transaction in the SA elements arises from. For example, the request for information gives clues to what the other agent is working on. The act of reporting on the status of various elements tells the recipient what the sender is aware of. Both parties are using the information for their own ends, integrated into their own schemata and reaching an individual interpretation. The transaction is an exchange rather than a sharing of awareness.

To summarise, the main difference between the DSA and shared SA approaches relates to the concepts of compatible and shared SA. The DSA approach postulates that, within collaborative systems, different team members have different, but compatible, SA regardless of whether the information that they have access to is the same or different. Shared SA accounts, on the other hand, suggest that some SA requirements are shared and, moreover, that efficient team performance is dependent upon team members having the same SA on shared SA requirements. Simply put, the DSA approach contends that, not only is this not the case, but also that this may not be possible (in some cases) furthermore, if it was the case then team performance may actually suffer rather than benefit.

Both approaches have their strengths and weaknesses. There can be little doubt that at least some proportion of the problem space can be tackled with a linear approach to SA and good results obtained (thus is well worth the effort). This leaves the remainder of the problem space and it is here that the DSA approach comes to the fore. The main strengths of the DSA model are related to the systemic approach that it advocates. First, the DSA approach takes the system itself as the unit of analysis rather than merely the individuals undertaking activity within it; it views SA as a non-linear, emergent property of collaborative systems. The systems thinking approach is one that has become accepted as an approach of considerable utility and is now prominent within human factors and ergonomics. Indeed, many have articulated the utility of taking the overall systems as the unit of analysis rather than the individuals within the system (e.g. Hutchins 1995, Hutchins and Klausen 1996, Ottino 2003, etc). Further, any SA description needs surely to consider the technological as well as human agents residing within the system and the SA-related information that they bring to the table. Viewing SA in this manner permits:

- a systemic description of the information comprising SA (which can be extrapolated to an individual SA level);
- judgements to be made on potential barriers to SA acquisition and maintenance;
- team SA within complex collaborative systems to be viewed in its entirety, rather than as its component parts (i.e. individual and shared team member SA);
- a beneficial side effect in that co-ordinated activity can be considered.

The DSA approach has a strong theoretical underpinning, notably schema theory (e.g. Neisser 1976), distributed cognition (Hutchins 1995) and cognitive systems engineering (Hollnagel 1998). In fact, one of the main criticisms of alternate SA models relates to their lack of theoretical underpinning (see below). In this case, the use of schema theory underlying the DSA concept gives the model a cyclical, parallel, generative nature, which serves to explain why individuals can predict before they perceive (because they have pre-existing schemata) and how individuals play a large part in creating better situations for themselves to be aware of (because the model is iterative and cyclical). Finally, the DSA approach is also amenable to accurate assessment. By gathering verbal transcripts, task analyses, interview and cognitive task analysis data, one can effectively determine what information was used by whom and what information was passed between different elements of the system. Taken collectively, this provides a very powerful description of system endeavour.

The main weaknesses of the DSA approach are related to its complexity and its measurement. The approach is more complex than other team SA models; the departure from thinking about individuals and what they know toward thinking about the system and what it knows is a difficult one to take. Further, since it is currently an emerging concept, much more investigation is required, although considerable evidence for the approach has been collected so far (e.g. Stanton *et al*. 2006, Walker *et al*. 2006, Salmon *et al*. 2008). Questions can also be raised over the methodological aspects of measuring DSA. First, unlike existing approaches such as SAGAT (Endsley 1995) and SART (Taylor 1990), the propositional network approach does not quantitatively assess the quality of the system's and individual agent's SA. Therefore, judgements on the quality of the system's DSA are made based on content analyses, task performance and subject matter experts (SMEs) and analyst subjective judgement. Second, the data used to identify the key information elements (e.g. verbal transcripts, critical decision method (CDM) interview response data, observation transcripts, etc.) can be criticised for their inability to identify the tacit SA-related knowledge (i.e. knowledge used but not openly expressed). However, these authors feel that the level of SME input reduces the potential for missing data in this case. Finally, when CDM data are used, it is typically collected post task performance and so could potentially suffer from the various problems associated with post-trial data collection, such as memory degradation (Klein and Armstrong 2004).

Endsley's shared SA view, on the other hand, takes its main strengths from the simplicity of its approach. The approach suggests that, in teams, some information requirements are distinct and some are shared or overlapping. On the face of it, this view is correct. At a very high level of analysis, teamwork consists of both teamwork tasks (tasks where individuals interact or coordinate behaviour to undertake tasks important to the team's goals) and task work tasks (tasks being performed by individual team members in light of their individual roles within the team) and so it is logical to assume that some SA requirements will be the same across team members and that some will be distinct. This view, however, does not consider how the different team members are using the information and also how their roles, tasks and experience impact their SA. The DSA approach contends that, in such cases, team member SA may be different even when they have access to the same information. Everything that is known about schema theory suggests that an individual's SA (regardless of whether the information used to build it is identical or is entirely different) will be highly personalised based on experience, goals, roles, tasks, knowledge and schemata. Of course, depending upon the environment under analysis, either approach may be correct; however, for complex modern day collaborative environments it is contended that more sophisticated approaches are required. Endsley's shared SA view also has an abundance of supporting research and has been applied in a wide variety of domains, including aviation maintenance (Endsley and Robertson 2000), the military (e.g. Endsley and Jones 1997, Riley *et al*. 2006), aviation and air traffic control (Farley *et al*. 2000) and process control (Kaber and Endsley 1998), to name only a few.

The main criticism of the shared SA approach concerns the concept of shared SA itself. According to Endsley and Robertson (2000), successful team performance requires that not only does each team member have good SA on his or her individual requirements, but also the same SA across shared SA requirements. It could be contended that not only is this almost impossible (due to the reasons cited above) it is also typically not required within collaborative systems. Further, the authors prefer to label shared SA requirements instead as transactive SA requirements in that the same information may be required by different team members, but it may often be used entirely differently. The very nature of team performance is such that different team members have different roles and so need to view and use information differently to other team members. As Gorman *et al*. (2006) point out, it does not make sense for everybody in a team to be aware of the same thing; rather; it is more important to ensure that the appropriate information is communicated to the appropriate team member at the right time.

Endsley's shared SA approach is also often criticised since it is based on her three-level model account of individual SA and therefore does not consider team performance and the interactions between team members in any great detail. Also, many have pointed out that the three-level model lacks a sound theoretical underpinning. For example, Smith and Hancock (1995) suggest that Endsley's reference to mental models, which themselves are ill defined, is problematic and Uhlarik and Comerford (2002) criticised Endsley's theory for its use of an information-processing model containing psychological constructs that are not yet fully understood and that are subject to great debate themselves. The shared SA view also has weaknesses related to its accompanying measurement approach. It is difficult to apply SAGAT during real-world collaborative tasks and also it is difficult to generate appropriate SA probes in complex systems where SA requirements may not be accurately discernable prior to task performance. Finally, Endsley's model can also be criticised due to its linear, feedback model of cognition approach.

7. Modelling DSA

The concept of DSA is not merely a theoretical construct and has been investigated by the authors in a number of civilian and military domains, including energy distribution (Salmon *et al*. 2008b), naval warfare (Stanton *et al*. 2006), airborne warning systems, railway maintenance (Walker *et al*. 2006), air traffic control and even driving (where the joint cognitive system of roads and other drivers are included; Walker *et al*. in press). The approach that has been used here to evaluate and represent DSA is known as the propositional network approach and is taken from the event analysis of systemic teamwork (Stanton *et al*. 2005) framework for analysing collaborative activities. In describing the awareness of a system, the propositional network approach uses networks of linked information elements (Stanton *et al*. 2006, Stewart *et al*. 2007). Network-based methods are nothing new in and of themselves, they are the mainstay of systems theoretic approaches. In the behavioural sciences a similar approach was applied by Anderson (1977), who used a network of structures to represent the development of a person's understanding. These information tokens represent what the agents involved 'need to know' in order to successfully undertake task performance and are linked based on the causal links that emerged during the scenario under analysis (e.g. contact 'has' heading, enemy 'has' plan, etc.). To demonstrate how these information networks are constructed, the following observational transcript can be used (example of a verbal transcript taken from a recent study on DSA in the energy distribution domain):

> **Preamble … Confirm time** of message (10:44). COCR gives **instructions** to SAP at XXXX **substation** . . . On **Supergrid Transformer circuit remove earths** busbar side of 280 at 280 **open earth switch** 281, remove **earths** adjacent to **132 Kv cable ends** adjacent **Supergrid Transformer**

2, **open earth switch** H21, end of **instructions**'... SAP reads back instructions to confirm receipt.

Within the extract the key words are highlighted in bold text. The resultant information network for this example is presented in Figure 3. In the authors' studies, people who were interviewed talk of every situation as if it were unique and in a way they are correct. After all, it is their genotype schema of a particular. Remember that Bartlett himself suggests that cricketers are unable to produce exactly the same cricket stroke (because of changes in the environment and schemata), so it is little surprise to record that no protocol from the authors' studies was identical either. Each transcript can be used to develop a representation of a phenotype schema.

It is possible to decompose the propositional network (which represents the system's SA) so that the SA of the individuals working in the system can be described. Thus, they can be used to gain insights into the different phenotype schemata that emerge from the interactions between the different agents in the system. With enough examples of these phenotype schemata (derived from interviews, reports, verbal and observational transcripts, task analyses, etc.) it is the authors' opinion that it could be possible to identify the invariants in the performance, which in turn could be used to describe the genotype schema. Whilst the phenotype structures are based on observation of the interactions, the genotypes are based on inferences about the likely underlying structures. This idea is explored further in the following case study.

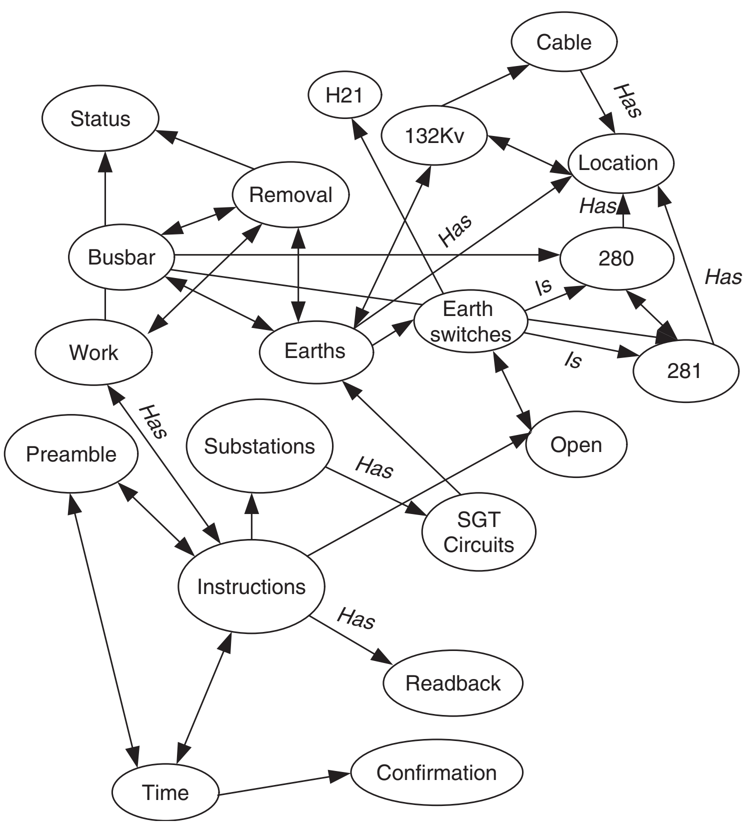

Figure 3. Example network extract for energy distribution scenario.

7.1. *Case study of compatible and transactive awareness in the energy distribution domain*

A recent analysis of maintenance scenarios in the UK energy distribution domain (see Salmon *et al.* 2008b) can be used to demonstrate the concepts of compatible and transactive SA. The activities in question were situated within the UK's electrical transmission network. Power stations (and feeds from continental Europe) energise the National Grid, who use an interconnected network of 400,000 volt (400 Kv), 275 Kv (the super grid network) and 132 Kv overhead lines and towers, or cables running in tunnels to carry electricity from source to substations. The substations are the distribution company's interface with regional electricity companies, who step down the grid's transmission voltages to 33 Kv 11 Kv, 400 v and 240 v for domestic and industrial consumption. The switching equipment at the substations is remotely manipulated from a central control centre to ensure that the capacity available in the grid is used in optimal and rational ways and that security of supply is maintained. Maintenance operations are also coordinated centrally from another centre, thereby separating operations from safety.

7.1.1. *Scenario*

The following example was derived from a 'return to service' scenario, which involved a 275 Kv circuit in North London following maintenance and the installation of new equipment. For the purposes of this example, the key personnel involved in this scenario were the central operations control room (COCR) operator, located at the central operations control room, a senior authorised persons (SAPs) and authorised persons (APs) sub-team located at a separate substation (there were also two other SAPs located at two other substations who were not observed) and an overhead line party working on the overhead lines. Ostensibly, the COCR operator took on the role of network commander, distributing work instructions to the SAPs located at the substations in the field and the overhead line party, who then undertook the required activities. The analyses were based on data collected during live observational study of the scenario. Two observers were located at the COCR, observing the COCR operator, and one observer was located in the field with the SAPs/APs at the substation where the work required was being undertaken. The data collected during the observations included a description of the activity (component task steps) performed by each of the agents involved, transcripts of the communications that occurred between agents during the scenarios, the technology used to mediate these communications, the artefacts used to aid task performance (e.g. tools, computers, instructions, substation diagrams, etc.), time and additional notes relating to the tasks being performed (e.g. why the task was being performed, what the outcomes were, etc.). Critical decision method (Klein and Armstrong 2004) interviews were conducted with key agents post scenario. For validation purposes, an SME from the energy distribution company reviewed the data collected and the subsequent analysis.

A propositional network for the entire scenario was created using the method described above and is presented in Figure 4. This represents a high-level depiction of the information elements comprising the system's DSA during the scenario.

Although the elements are identified in Figure 4, this does not show how they are distributed around the agents comprising the team involved. An indication of this distribution is given in Figure 5, in which the information elements are classified into four types. Those elements belonging to each of the three sub-teams (i.e. the COCR operator, the SAP and AP working at the substation and the overhead line party working on the overhead lines) and a fourth type, where the same element is used by more than one sub-team. The three different codes indicate the compatible elements in DSA, i.e. those elements that are required by each sub-team, that are different to the other sub-teams, but necessary for the system to work. The compatibility of the elements indicates that these elements are not in conflict; rather, they indicate the different purposes (and therefore different schemata that will be brought to bear). The fourth category of information element is those transactional elements that pass between sub-teams. As with general systems theoretic principles, the transaction between systems elements implies some sort of conversion of the information received, meaning that information elements will undergo change when they are used by a new part of the system. This change will include the way it is combined with other information elements and the meaning that is applied to it in the context of the goals of the sub-team.

The ownership of the information elements is further explored in Table 1; this shows the sub-teams, their tasks and the information elements that they use in pursuit of their goals. The knowledge elements active for the different team roles (shown in the vertical columns) represent the genotypical state of SA at the level of the individual. Where situational elements are matched in the horizontal plane across all team roles, these elements can be regarded as invariants and can be viewed as the genotypical state of 'systemic' SA.

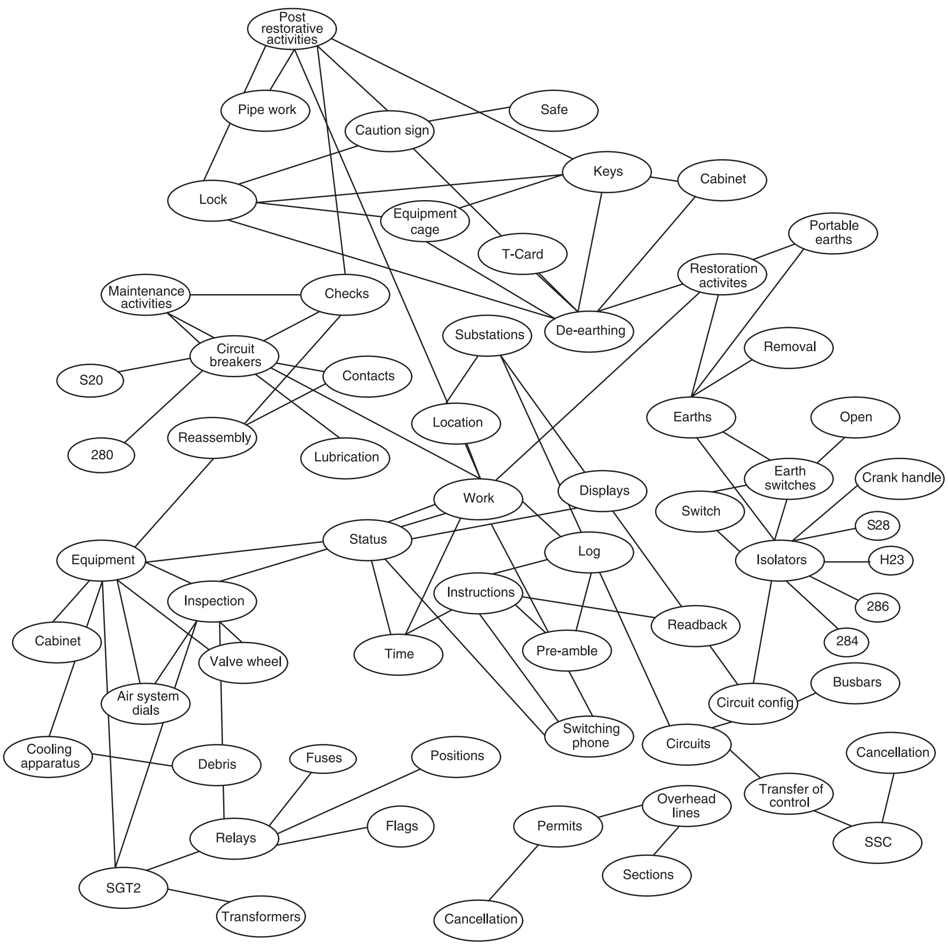

Figure 4. DSA for return to service scenario.

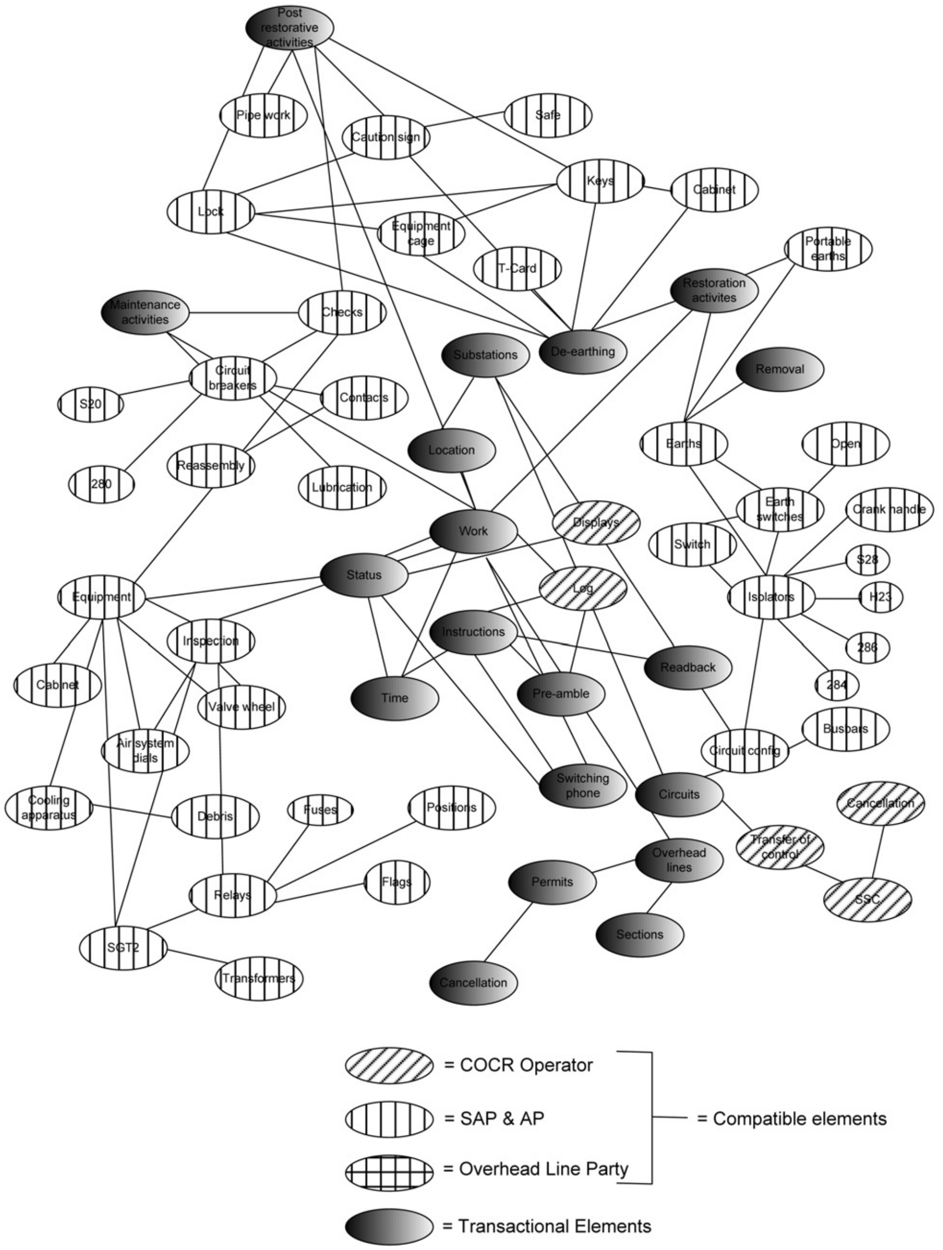

Figure 5. Compatible and transactive elements during return to service scenario. COCR = central operations control room; SAP = senior authorised person; AP = authorised person.

As Table 1 shows, there are 60 information tokens in total, 19 of which are transactive (that is, elements that are common to two or more team roles). When people talk of 'shared awareness', they are probably referring to the use of information that they consider to be identical, such as the information relating to the work status or work instructions as identified in this example. However, whilst it is not argued that the information in this case is related to the same work being undertaken, it is apparent that each component of the

Table 1. Active situation elements for each team role (the team genotype), the invariants across all team roles (the systemic genotype) and the various 'transactions' between team roles.

	SAP/AP	COCR	Overhead Line Party	
Substations		Transaction	Transaction	Substations
Work		Transaction	Transaction	Work
Location		Transaction	Transaction	Location
Instructions		Transaction	Transaction	Instructions
Preamble		Transaction	Transaction	Preamble
Log				
Status		Transaction	Transaction	Status
Time		Transaction	Transaction	Time
Displays				
Readback		Transaction	Transaction	Readback
Maintenance activities		Transaction	Transaction	Maintenance activities
Circuits		Transaction	Transaction	Circuits
Circuit breakers				
Checks				
S20				
280				
Reassembly				
Lubrication				
Contacts				
Equipment				
Cabinet				
Inspection				
Valve wheel				
Cooling apparatus				
Air system dials				
Valve wheel				
Debris				
SGT2				
Transformers				
Relays				
Fuses				
Positions				
Flags				
Switching phone		Transaction		
Permits		Transaction	Transaction	
Cancellation			Transaction	
Overhead lines			Transaction	
Sections			Transaction	
Transfer of control				
System state cert				
Circuit configuration				
Busbars				
Isolators (S28, H23, 286, 284)				
Earths				
Earth switches				
Switch				
Open				
Crank handle				
Removal		Transaction	Transaction	Removal
De-earthing		Transaction	Transaction	De-earthing
Restoration		Transaction	Transaction	Restoration
Portable earths				
Post-restorative activities		Transaction	Transaction	Post-restorative activities
Lock				
Keys				
T-card				
Equipment cage				
Safe				
Caution sign				
Pipe work				

SYSTEM GENOTYPE

SAP/AP Genotype | COCR Genotype | Overhead Line Party Genotype

Note: SAP = senior authorised person; AP = authorised person; COCR = central operations control room.

system places a rather different meaning and understanding on the work status and work instructions. They are using different genotype schemata to interpret the information and producing different phenotype schemata to pick up information and perform activities related to their tasks and goals. Thus, one should be talking in terms of compatible and transactive elements within a general framework of DSA.

The concepts of transactive and compatible SA elements can be explored further by looking at the propositional networks and information elements in more detail. For example, Figure 6 presents a snapshot of the SA and activities at different points in time in the scenario. (On the left-hand side of Figure 8 the task in question is described). The information networks presented on the right-hand side of the figure depict the information elements comprising SA. Within the information network, those information elements that represent transactional and compatible SA are identified.

7.1.2. *Distribution of work instructions*

During the distribution of work instructions, the SAP at substation A is given the earth removal instructions by the COCR operator. Initially, the SAP and COCR operator take part in a preamble and once the instructions have been issued, the SAP has to read back the instructions to the COCR in order to confirm successful receipt of them. The information elements preamble and readback are therefore representative of transactive SA elements. All of the other elements, including time, location, instructions and the circuits involved, are representative of both transactive and compatible SA, since they are discussed in the context of the work instructions (transactions) but are viewed differently by the SAP and COCR due to their different goals.

7.1.3. *Removal of earths*

During the performance of the earth removal, the SAP at substation A undertakes the required activities whilst the COCR operator is engaged in other command activities in the control room. All of the information elements are therefore compatible, meaning that the SAP and COCR operator had different, but requisite, SA during the activities. For example, the COCR operator's SA consisted of a high-level picture of the various activities being undertaken (e.g. who was doing what, what they were doing and why and what they would be doing next), whilst the SAP's SA was related specifically to his activities at the substation. Thus, although each agent held a different view of the situation, it was compatible with the SAP's SA, in that each agent's SA formed a composite part of the DSA of the entire network and was required collectively for the entire system to work.

7.1.4. *Work status reporting*

In the final information network, the SAP contacts the COCR operator to confirm that he has completed the removal of earths task. The COCR operator thus receives a 'transaction' of the SAP's SA via the work status report. In this case, then, the elements related to the removal activities (e.g. paperwork, circuit breakers, inspection, lock, earth switches, etc.) are representative of compatible SA elements since each SAP has a local and different SA of them at their specific substation; however, the collective awareness of the three SAPs is required for the overall activity to be undertaken successfully. The transactive SA elements during this portion of the task are work progress, time and

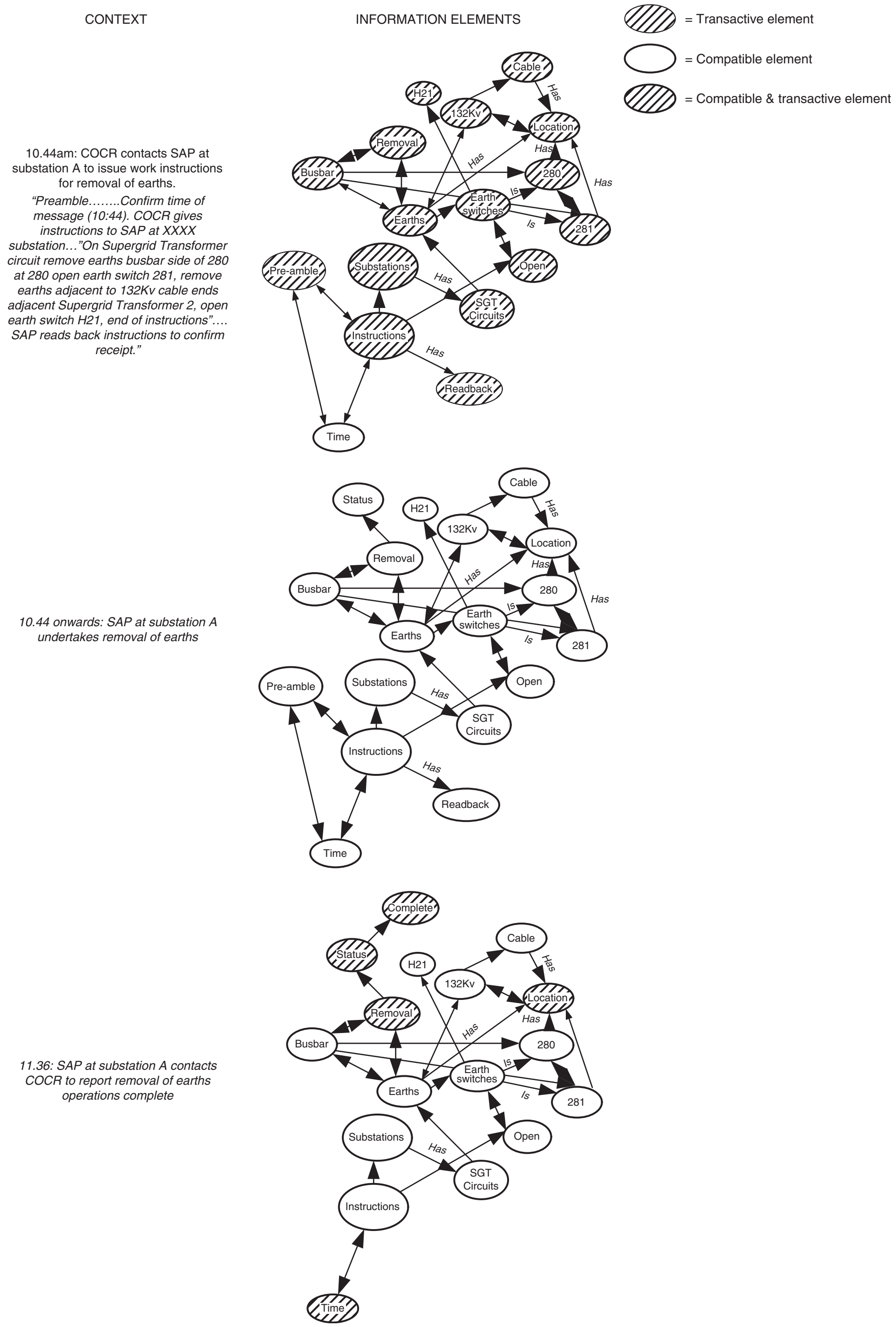

Figure 6. Transactive and compatible SA during return to service scenario. SAP = senior authorised person; COCR = central operations control room.

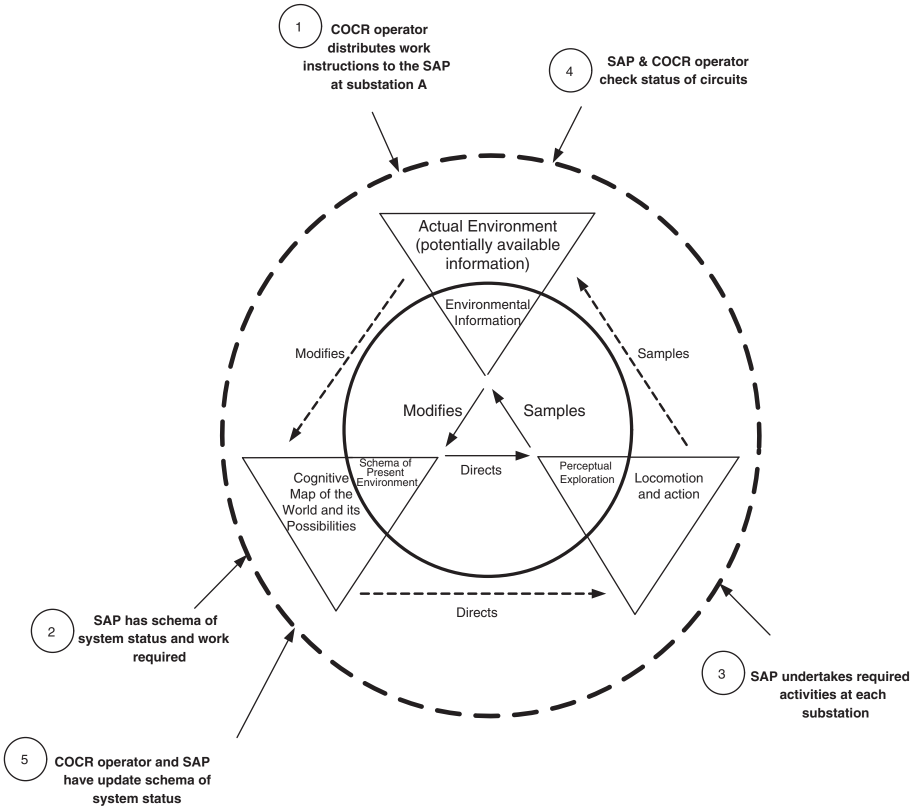

Figure 7. System perceptual cycle distributed SA example. COCR = central operations control room; SAP = senior authorised person.

location, since they are communicated from the SAPs to the COCR operator during work progress updates. This example therefore demonstrates how each agent's SA is different but compatible and also how transactions update the system's SA and serve to prompt further actions.

The COCR operator has SA of the overall ongoing work activities whereas each SAP in the field has SA related to the work that they are undertaking. Each portion of SA is therefore different but compatible and is required collectively for the system to work. These concepts can be demonstrated further by overlaying the energy distribution systems activities onto Smith and Hancock's perceptual cycle model of SA. This is presented in Figure 7.

Figure 7 demonstrates how the activities and SA transactions occurring within the energy distribution system can be mapped onto the perceptual cycle model. The first transaction to take place is the issue of instructions by the COCR operator. This serves to update each SAP's schema of the system and of the work required, which in turn drives the activities that the system then undertakes. The outcome of these activities is then checked by the SAPs in the field and the COCR at the control centre (via circuit displays), which in turn modifies both the systems and the SAPs and COCR schema of the current status of the system. The examples presented demonstrate how the cyclical perception-action notion can be applied to the entire system as well as the teams and individuals working within it. The COCR and the SAPs involved each initiate SA transactions regarding the state of the

Distinct Individual SA Requirements	Shared SA Requirements
COCR Operator	- Instructions
- Maintenance activities	- Maintenance activities
- Restoration activities	- Restoration activities
- Post restorative activities	- Post restorative activities
- Time	- Locations
- Displays	- Removal
- Log	- Work
- Transfer of control	- Work status
	- Time
SAP/AP	- Pre-amble
- Pipe work	- Readback
- Caution sign	- Switching phone
- Lock	- Circuits
- Safe	- Permits
- Equipment cage	- Overhead lines
- Keys	- Sections
- Cabinet	- Cancellation
- T-Card	
- Portable earths	
- Checks	
- Circuit breakers	
- S20	
- Contacts	
- 280	
- Reassembly	
- Lubrication	
- Equipment	
- Cabinet	
- Air system dials	
- Valve wheel	
- Cooling apparatus	
- Debris	
- Fuses	
- Positions	
- Relays	
- Super grid transformers	
- Flags	
- Circuit configuration	
- Busbars	
- Isolators	
- Earths & Portable earths	
- Earth switches	
- Open	
- Crank handles	
Overhead Line Party Contact	
- N/A	

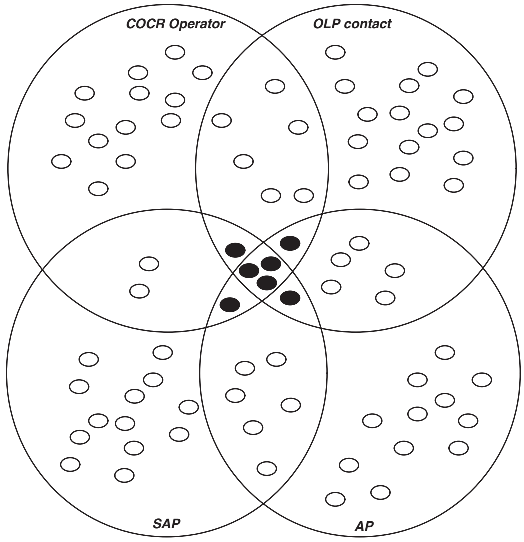

Figure 8. Shared SA perspective. COCR = central operations control room; SAP = senior authorised person; AP = authorised person; OLP = overhead line party.

environment that serve to initiate action of some sort, which in turn modifies other agents' and the system's schema, which in turn initiates further action and also further transactions regarding the state of the system's schema.

It is also instructive to consider how shared SA approaches would view the scenario. Endsley's shared SA model (chosen because of its popularity), would typically use goal-directed task analysis to identify SA requirements (in the form of SA elements) prior to task performance followed by SAGAT approach to assess team members' perception, comprehension and projection of these SA elements. Subsequent comparisons would then be made on the extent to which team member SA was the same on those SA requirements that were shared. As a starting point in this comparison, it is notable that a SAGAT-based assessment of SA during the scenarios in question was not possible. The scenarios were real-world scenarios and so could not be frozen in order to administer queries; nor could queries have been easily administered on-line during task performance. In suggesting how shared SA models would represent this example, one can only assume that a judgement would have to be made on what SA elements were shared and what SA elements were distinct. A representation of how shared SA models may view this example is presented in Figure 8.

This case study has illustrated some of the basic concepts in the DSA approach. It demonstrates the phenotypical nature of knowledge activation for individual team roles; that is, their present situational reality and the extent to which that situation differs from other team members. The case study also shows where these phenotypical states have interfaced with other phenotypical states in the form of transactions. Again, the point is made that what one element means within one team member's situational model is likely to be quite different from another's. This fact does not, however, diminish its 'compatibility'. Having identified the heterogeneous nature of transactive SA, at the level of the individual, the case study has also highlighted the homogenous nature of SA at the level of the system. Some situational elements are invariants across all actors. Whilst each actor will place their own meaning on these elements and use them for different means, the invariant nature of them permits diagnosis of the overall genotypical state of a system's SA, as an emergent property of its component/individual states. In principle, this paves the way for diagnosis of how that state is achieved and maintained.

The case study presented has explored in more detail not just the presence of transactive SA elements but also their precise nature within a specific context. It has also sought to illustrate, again in more detail, the cyclical rather than linear nature of systemic SA and it is readily apparent that complex distributed systems perform in this manner. The case study also highlights the role of network-based methodologies as a means of describing and representing this phenomenon and, in doing so, creates a theoretical and methodological perspective quite apart from the prevailing state of the art in SA research.

8. Conclusions

The purpose of this article was to attempt to formulate an account of SA in collaborative environments using the ideas of genotype and phenotype schemata and the perceptual cycle model proposed by Niesser (1976) and to further explore the concepts of transactive and compatible SA outlined by Salmon *et al.* (2008a). Whilst the ideas presented in this article are quite different to those expressed by the dominant models of individual and team SA presented in the literature (e.g. Endsley 1995, Endsley and Jones 1997), it is contended that that they are more appropriate for the study of SA in collaborative environments. The schema-based amount of SA in collaborative environments affects existing models in four critical ways.

First, using schema theory as the basis, it is argued here that individual team members experience a situation in different ways and therefore that their awareness is compatible rather than shared. Each team member's SA is defined by their own personal experience, goals, roles, training, knowledge, skills and so on. 'The situation' can indeed be objectively defined in all manner of ways but under a schema/systems perspective there is a certain futility in this. Instead, SA is argued as being a systemic property (herein this is called the phenotype), which is the product rather than the sum of each individual's schema-based 'theory of the world' (herein called the genotype). This sort of heterogeneity, in systems terms, far from being an analytical inconvenience, is actually a strength, for it is this property that gives rise to emergence and the sort of synergistic SA that is surely the point of the entire team-working endeavour.

Second, this account is in direct contradiction to those that suggest teams possess 'shared SA' (which tacitly assumes 'identical' awareness and an objectively definable situation). The DSA approach suggests that teams instead hold compatible and transactive SA. Within collaborative systems, each team member does not need to know everything; rather, they possess the SA that they need for their specific task. Yet they are also cognisant of what other team members need to know and do know. Although different team members may be aware of the same information, this awareness is not shared, since the team members often have different goals and so view the situation differently based on their own task and goals. Each team member's SA is, however, compatible. This is the nub of DSA. It is different in content but is compatible in that it is collectively needed for the team to perform the collaborative task successfully. On the one hand it could be argued as to how all these individual heterogeneous experiences of the situation ever coalesce into something meaningful. The inconvenient truth, as it were, is simply that they do (as the case study shows).

This paper puts forward the idea of transactive SA, third, as the means by which this occurs. Transactive SA focuses on transactions. Elements and entities from one model of a situation can form an interacting part of another without any necessary requirement for parity of meaning or purpose. As stated above, it is the systemic 'transformation' of situational elements as they cross the system boundary from one team member to another that bestows upon team SA an emergent behaviour. The analytic and methodological challenge seems to be to ensure that this emergent behaviour is 'desirable'.

Fourth and finally, it is argued that there is significant utility in the progression from linear, feedback models of cognition (of the sort that underlie Endlsey's three-level model) in favour of a cyclical, parallel, generative model based on schema theory. This is a model that helps to explain why individuals can predict before they perceive (because they have pre-existing schemata), why less conscious reporting of SA probes can mean better SA (because schemata are often not available for conscious inspection and retrospective recall) and how individuals play a large part in creating better situations for themselves to be aware of (because the model is iterative and cyclical). The intuitive appeal of this approach is borne out in the case studies and further highlighted deterministic models of SA to the probabilistic behaviour of teams.

To conclude, the purpose of this paper was to introduce the ideas surrounding DSA in command and control teams and the sub-concept of compatible and transactive SA elements. To this end, schema theory is advanced as an underlying theoretical perspective, the perceptual cycle as a useful conceptual model, compatible and transactive SA as specific mechanisms and phenotypical and genotypical SA as psychological constructs. Building on the work of Bartlett (1932), Neisser (1976), Norman and Shallice (1986), Adams *et al.* (1995), and Smith and Hancock (1995) offers, the authors hope, the possibility of moving SA to the next level, one more pertinent to the challenges raised by team working.

Acknowledgements

This work from the Human Factors Integration Defence Technology Centre was part funded by the Human Sciences Domain of the UK Ministry of Defence Scientific Research Programme. The authors are grateful to their colleagues for their support and encouragement, in particular to (in alphabetical order) Dr Chris Baber, Dr Don Harris, Dr Rob Houghton, Richard McMaster, Rebecca Stewart and Dr Mark Young, and would also like to thank the staff at the energy distribution company for their assistance in allowing us to study the scenarios involved in this research.

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About the authors

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Dr Guy Walker gained his PhD in Ergonomics in 2002 and since then has been engaged on a wide variety of human factors projects both in industry and academia. These have included safety critical train protection and warning system design, vehicle automation and feedback, air traffic control, process control and advanced driver training. Guy's current research interests are orientated around his current role as Research Fellow within the HFI-DTC consortium and the application of open systems concepts to command and control. Guy is author of more than 30 journal articles and co-author of *Human Factors Methods: A Practical Guide for Engineering and Design*.

Dan Jenkins graduated in 2004 from Brunel University with an MEng (Hons) in Mechanical Engineering and Design, receiving the University Prize for top student in the department. With over two years' experience as a design engineer in the automotive industry, Dan has worked in a number of roles throughout the world. This wide range of placements has developed experience encompassing design, engineering, project management and commercial awareness. Both academically and within industry Dan has always had a strong focus on customer-orientated design, design for inclusion and human factors. Completed projects include a thesis for Ford Motor Company investigating 'Why drivers sit as they do in the modern automobile' and a Masters thesis designing and developing a system to raise driver situational awareness and reduce lateral collisions. Dan is currently a full-time research fellow on the HFI-DTC project and is studying for a PhD related to the project.